The masses of vector supermultiplet and of the Higgs supertriplet in supersymmetric $SU(5)$ model

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Abstract

The masses of vector supermultiplet and of the Higgs supertriplet in standard supersymmetric $SU(5)$ model are calculated. Taking into account uncertainties related with the initial coupling constants and threshold corrections we find that in standard supersymmetric $SU(5)$ model the scale of the supersymmetry breaking could be up to 50 Tev. We find that in the extensions of the standard SU(5) supersymmetric model it is possible to increase the supersymmetry breaking scale up to $O(10^{12})$ Gev. In standard $SU(5)$ supersymmetric model it is possible to increase the GUT scale up to $5 \cdot 10^{17}$ Gev provided that the masses of chiral superoctets and supertriplets are $m_{3,8} \sim O(10^{13}) Gev$. We also propose SU(5) supersymmetric model with 6 light superdoublets and superoctet with a mass $O(10^9)$ Gev.

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There has recently been renewed interest [1]-[12] in grand unification business related with the recent LEP data which allow to measure $\sin^2(\theta_w)$ with unprecendented accuracy. Namely, the world averages with the LEP data mean that the standard nonsupersymmetric $SU(5)$ model [13] is ruled out finally and forever (the fact that the standard $SU(5)$ model is in conflict with experiment was well known [14, 15] before the LEP data) but maybe the most striking and impressive lesson from LEP is that the supersymmetric extension of the standard $SU(5)$ model [16]-[18] predicts the Weinberg angle θ_w in good agreement with experiment. The remarkable success of the supersymmetric $SU(5)$ model is considered by many physicists as the first hint in favour of the existence of low energy broken supersymmetry in nature. A natural question arises: is it possible to invent nonsupersymmetric generalizations of the standard $SU(5)$ model nonconfronting the experimental data or to increase the supersymmetry breaking scale significantly. In the $SO(10)$ model the introduction of the intermediate scale $M_I \sim 10^{11} Gev$ allows to obtain the Weinberg angle θ_w in agreement with experiment [19]. In refs.[20, 21] it has been proposed to cure the problems of the standard $SU(5)$ model by the introduction of the additional split multiplets $5 \oplus \overline{5}$ and $10 \oplus \overline{10}$ in the minimal $3(\overline{5} \oplus 10)$ of the $SU(5)$ model. In ref.[22] the extension of the standard $SU(5)$ model with light scalar coloured octets and electroweak triplets has been proposed.

In this paper we discuss the coupling constant unification in standard supersymmetric $SU(5)$ model and its extensions. Namely, we calculate the masses of two key parameters of SU(5) supersymmetric model - the mass of vector supermultiplet and the mass of the Higgs supertriplet. In supersymmetric SU(5) model both vector supermultiplet and the Higgs supertriplet are responsible for the proton decay. Taking into account uncertainties associated with the initial gauge coupling constants and threshold corrections we conclude that in standard supersymmetric $SU(5)$ model the scale of the supersymmetry breaking could be up to 50 Tev. We find that in the extensions of the standard $SU(5)$ supersymmetric model it is possible to increase the supersymmetry breaking scale up to 10^{12} Gev. In standard SU(5) supersymmetric model it is possible to increase GUT scale up to $5 \cdot 10^{17}$ Gev provided that the masses of chiral superoctets and supertriplets

$m_{3,8} \sim O(10^{13})$ Gev. We also propose SU(5) supersymmetric model with 6 light Higgs superdoublets and superoctet with a mass $O(10^9)$ Gev.

The standard supersymmetric $SU(5)$ model [16]-[18] contains three light supermatter generations and two light superhiggs doublets. A minimal choice of massive supermultiplets at the high scale is $(\overline{3}, 2, \frac{5}{2}) \oplus c.c.$ massive vector supermultiplet with the mass M_v, massive chiral supermultiplets $(8,1,0), (1,3,0), (1,1,0)$ with the masses m_8, m_3, m_1 (embeded in a 24 supermultiplet of $SU(5)$) and a $(3, 1, -\frac{1}{3}) \oplus (-3, 1, \frac{1}{3})$ complex Higgs supertriplet with a mass M_3 embeded in $5 \oplus \overline{5}$ supermultiplet of $SU(5)$. In low energy spectrum we have squark and slepton multiplets $(\tilde{u}, \tilde{d})_L, \tilde{u}^c_L, \tilde{d}^c_L, (\tilde{\nu}, \tilde{e})_L, \tilde{e}^c_L$ plus the corresponding squarks and sleptons of the second and third generations. Besides in the low energy spectrum we have $SU(3)$ octet of gluino with a mass $m_{\tilde{g}}$, triplet of $SU(2)$ gaugino with a mass $m_{\tilde{w}}$ and the $U(1)$ gaugino with a mass $m_{\tilde{\gamma}}$. For the energies between M_z and M_{GUT} we have effective $SU(3) \otimes SU(2) \otimes U(1)$ gauge theory. In one loop approximation the corresponding solutions of the renormalization group equations are well known [18]. In our paper instead of the prediction of $\sin^2(\theta_w)$ following refs.[6, 23, 24] we consider the following one loop relations between the effective gauge coupling constants, the mass of the vector massive supermultiplet M_v and the mass of the superhiggs triplet M_3:

$$A \equiv 2(\frac{1}{\alpha_1(m_t)} - \frac{1}{\alpha_3(m_t)}) + 3(\frac{1}{\alpha_1(m_t)} - \frac{1}{\alpha_2(m_t)}) = \Delta_A, \tag{1}$$

$$B \equiv 2(\frac{1}{\alpha_1(m_t)} - \frac{1}{\alpha 3(m_t)}) - 3(\frac{1}{\alpha_1(m_t)} - \frac{1}{\alpha_2(m_t)}) = \Delta_B, \tag{2}$$

where

$$\Delta_A = (\frac{1}{2\pi})(\delta_{1A} + \delta_{2A} + \delta_{3A}), \tag{3}$$

$$\Delta_B = (\frac{1}{2\pi})(\delta_{1B} + \delta_{2B} + \delta_{3B}), \tag{4}$$

$$\delta_{1A} = 44ln(\frac{M_v}{m_t}) - 4ln(\frac{M_v}{m_{\tilde{g}}}) - 4ln(\frac{M_v}{m_{\tilde{w}}}), \tag{5}$$

$$\delta_{2A} = -6(ln(\frac{M_v}{m_8}) + ln(\frac{M_v}{m_3})), \tag{6}$$

$$\delta_{3A} = 6ln(m_{(\tilde{u},\tilde{d})_L}) - 3ln(m_{\tilde{u}^c_L}) - 3ln(m_{\tilde{e}^c_L}), \tag{7}$$

$$\delta_{1B} = 0.4ln(\frac{M_3}{m_h}) + 0.4ln(\frac{M_3}{m_H}) + 1.6ln(\frac{M_3}{m_{sh}}), \tag{8}$$

$$\delta_{2B} = 4ln(\frac{m_{\tilde{g}}}{m_{\tilde{w}}}) + 6ln(\frac{m_8}{m_3}), \quad (9)$$

$$5\delta_{3B} = -12ln(m_{(\tilde{u},\tilde{d})_L}) + 9ln(m_{\tilde{u}^c_L}) + 6ln(m_{\tilde{d}^c_L}) - 6ln(m_{(\tilde{\nu},\tilde{e})_L}) + 3ln(m_{\tilde{e}^c_L}) \quad (10)$$

Here m_h, m_H and m_{sh} are the masses of the first light Higgs isodoublet, the second Higgs isodoublet and the isodoublet of superhiggses. The relations (1-10) are very convenient since they allow to determine separately two key parameters of the high energy spectrum of $SU(5)$ model, the mass of the vector supermultiplet M_v and the mass of the chiral supertriplet M_3. Both the vector supermultiplet and the chiral supertriplet are responsible for the proton decay in supersymmetric $SU(5)$ model [18]. In standard nonsupersymmetric $SU(5)$ model the proton lifetime due to the massive vector exchange is determined by the formula [25]

$$\Gamma(p \to e^+\pi^o)^{-1} = 4 \cdot 10^{29\pm0.7}(\frac{M_v}{2 \cdot 10^{14}Gev})^4 yr \quad (11)$$

In supersymmetric $SU(5)$ model the GUT coupling constant is $\alpha_{GUT} \approx \frac{1}{25}$ compared to $\alpha_{GUT} \approx \frac{1}{41}$ in standard $SU(5)$ model, so we have to multiply the expression (11) by factor $(\frac{25}{41})^2$. From the current experimental limit [26] $\Gamma(p \to e^+\pi^o)^{-1} \geq 9 \cdot 10^{32}yr$ we conclude that $M_v \geq 1.3 \cdot 10^{15}Gev$. The corresponding experimental bound on the mass of the superhiggs triplet M_3 depends on the masses of gaugino and squarks [27, 28, 5]. In our calculations we use the following values for the initial coupling constants [26,29 - 32]:

$$\alpha_3(M_z)_{\overline{MS}} = 0.118 \pm 0.03, \quad (12)$$

$$\sin^2_{\overline{MS}}(\theta_w)(M_z) = 0.2320 \pm 0.0005, \quad (13)$$

$$(\alpha_{em,\overline{MS}}(M_z))^{-1} = 127.79 \pm 0.13 \quad (14)$$

For the top quark mass $m_t = 175 \pm 6$ Gev [33] after the solution of the corresponding renormalization group equations in the region $M_z \leq E \leq m_t$ we find that in the $\overline{MS}$-scheme

$$A_{\overline{MS}} = 183.96 \pm 0.47, \quad (15)$$

$$B_{\overline{MS}} = 13.02 \pm 0.45 \quad (16)$$

Here the errors in formulae (15,16) are determined mainly by the error in the determination of the strong coupling constant $\alpha_s(M_Z)$. Since we study the SU(5) supersymmetric

model the more appropriate is to use the $\overline{DR}$-scheme. The relation between the coupling constants in the $\overline{MS}$- and $\overline{DR}$-schemes has the form [34]

$$\frac{1}{\alpha_{i_{\overline{MS}}}} = \frac{1}{\alpha_{i_{\overline{DR}}}} + \frac{C_2(G)}{12\pi}, \tag{17}$$

where $C_2(G)$ is the quadratic casimir operator for the adjoint representation. In the $\overline{DR}$-scheme we find that

$$A_{\overline{DR}} = A_{\overline{MS}} + \frac{1}{\pi} = 184.28 \pm 0.47, \tag{18}$$

$$B_{\overline{DR}} = B_{\overline{MS}} = 13.02 \pm 0.45 \tag{19}$$

Using one loop formulae (1-10) in the neglection of the contributions due to spaticle mass differences and high scale threshold corrections ($\delta_{2A} = \delta_{2B} = \delta_{3A} = \delta_{3B} = 0$ we find that

$$M_v = 1.79 (\frac{175Gev}{M_{SUSY}})^{\frac{2}{9}} \cdot 10^{16 \pm 0.04} Gev, \tag{20}$$

$$M_3 = 1.1 \frac{M_{h,eff}}{175Gev} \cdot 10^{17 \pm 0.5} Gev, \tag{21}$$

where $M_{SUSY} \equiv (m_{\tilde{g}} m_{\tilde{w}})^{\frac{1}{2}}$ and $M_{h,eff} \equiv (m_h m_H)^{\frac{1}{6}} m_{s,h}^{\frac{2}{3}}$.

An account of two loop corrections in neglection of the top quark Yukawa coupling constant leads to the appearance of the additional factors

$$\delta_{4A,4B} = 2(\theta_1 - \theta_3) \pm 3(\theta_1 - \theta_3), \tag{22}$$

in the right hand side of the expressions (3,4). Here

$$\theta_i = \frac{1}{4\pi} \sum_{j=1}^{3} \frac{b_{ij}}{b_j} ln[\frac{\alpha_j(M_v)}{\alpha_j(m_t)}] \tag{23}$$

and b_i, b_{ij} are the one loop, two loop β function coefficients. An account of two loop corrections (22) leads to the increase of M_v by factor 1.2 and the decrease of M_3 by factor 56. An account of two loop corrections due to nonzero top quark Yukawa coupling constant as it has been found in ref.[11] leads to the additional negative corrections to one loop beta function coefficients

$$b_i \rightarrow b_i - b_{i;top} \frac{h_t^2}{16\pi^2}, \tag{24}$$

where $b_{i;top} = \frac{26}{5}, 6, 4$ for $i = 1, 2, 3$. We have found that an account of two loop Yukawa corrections practically does not change the value of M_v and leads to the small increase of M_3 by factor 1.5(1.2) for $h_t(m_t) = 1$ ($h_t(m_t) = 0.8$). In the assumption that all gaugino masses coincide at GUT scale we find standard relation $m_{\tilde{g}} = \frac{\alpha_3(M_{SUSY})}{\alpha_2(M_{SUSY})} m_{\tilde{w}} = (2.2 \div 2.5) m_{\tilde{w}}$ between gluino and wino masses that leads to the decrease of M_3 by factor $3.7 \div 4.6$. We have found that the values of δ_{3B} (δ_{3A}) for realistic spectrum are between 0 and 0.4 (0 and 5.5) that leads to the maximal decrease of M_3 (M_v) by factor 1.5 (1.4). Taking into account these corrections we find that

$$M_v = 2.0 \cdot (1 \div 0.67) \cdot (\frac{175 Gev}{M_{SUSY}})^{\frac{2}{9}} \cdot 10^{16 \pm 0.04} Gev, \tag{25}$$

$$M_3 = 0.80 \cdot (1 \div 0.43) \cdot \frac{M_{h,eff}}{175 Gev} 10^{15 \pm 0.5} Gev \tag{26}$$

It should be noted that the estimates (25,26) are obtained in the assumption $M_v = m_3 = m_8$.

From the lower bound $1.3 \cdot 10^{15}$ Gev on the value of the mass of the vector bosons responsible for the baryon number nonconservation we find an upper bound on the value of the supersymmetry breaking parameter $M_{SUSY} \leq 1 \cdot 10^8 Gev$. Let us consider now the equations (2,8,10,26). For the lightest Higgs mass $m_h = 100$ Gev in the assumption that $m_H = m_{sh} = M_{SUSY}$ and $M_3 \leq 3 M_v$ [5] [1] we find that

$$M_{SUSY} \leq 50 Tev \tag{27}$$

The proton lifetime due to the exchange of the Higgs supertriplet predicts much shorter lifetimes for the mode $p \to \overline{\nu} K^+$ than the standard vector boson exchange which leads to the $p \to e^+ \pi^0$ proton decay. From the nonobservation of $p \to \overline{\nu} K^+$ decay Arnowitt and Nath [5] derived an upper limit on the parameter C which can be rewritten in the form

$$C \leq 335 \cdot \frac{M_3}{6 \cdot 10^{16} Gev} \cdot Gev^{-1}, \tag{28}$$

$$C = \frac{-2\alpha_2}{\alpha_3 \sin(2\beta)} \frac{m_{\tilde{g}}}{m_{\tilde{q}}^2} \cdot 10^6 Gev^{-1} \tag{29}$$

[1] The inequality $M_3 \leq 3 M_v$ comes from the requirement of the absence of Landau pole singularities for effective charges for energies up to Planck mass.

From the equations (26,28,29) we find that

$$\frac{m_{\tilde{g}}}{m_{\tilde{q}}^2 M_{h,eff}} \leq 84 \cdot 10^{-9} Gev^{-2} \tag{30}$$

From the inequality (30) and from the experimental bound [33] $m_{\tilde{g}} \geq 168 Gev$ on the gluino mass in the assumption that $m_{\tilde{q}} = m_H = m_{sh}$ we find bound on squark mass

$$m_{\tilde{q}} \geq 1460 Gev \tag{31}$$

It should be noted that up to now we assumed that at GUT scale all gaugino masses coincide. If we refuse from this requirement it is possible to increase the supertriplet mass M_3 since M_3 is proportional to $(\frac{m_{\tilde{w}}}{m_{\tilde{g}}})^{\frac{5}{3}}$. For instance, for $m_{\tilde{g}} = m_{\tilde{w}}$ we find that M_3 could be up to $5.4 \cdot 10^{16} Gev$ and as a consequence we have more weak bound $m_{\tilde{q}} \geq 920 Gev$ for squark mass. Besides for $m_8 \neq m_3$ we have additional factor $(\frac{m_3}{m_8})^{\frac{5}{3}}$ in front of the expression for the determination of M_3 that allows to increase the value of M_3.

It is instructive to consider the supersymmetric $SU(5)$ model with relatively light coloured octet and triplets [23]. For instance, consider the superpotential

$$W = \lambda \sigma(x)[Tr(\Phi^2(x)) - c^2], \tag{32}$$

where $\sigma(x)$ is the $SU(5)$ singlet chiral superfield and $\Phi(x)$ is chiral 24-plet in the adjoint representation. For the superpotential (32) the coloured octet and electroweak triplet superfields remain massless after $SU(5)$ gauge symmetry breaking and they acquire the masses $O(M_{SUSY})$ after the supersymmetry breaking. So in this scenario we have additional relatively light fields. Lower bound on the mass of the vector bosons leads to the bound on the supersummetry breaking scale $M_{SUSY} \leq O(10^{12})$ Gev. In order to satisfy the second equation for the mass of the Higgs triplets let us introduce in the model two additional superhiggs 5-plets. If we assume that after $SU(5)$ gauge symmetry breaking the corresponding Higgs triplets acquire mass $O(M_v)$, the light Higgs isodoublet has a mass $O(M_z)$, the second Higgs isodoublet and superhiggses have masses $O(M_{SUSY})$ then we can satisfy the equation (2) for $M_{SUSY} \sim 10^{12} Gev$.

In standard supersymmetric SU(5) model the superpotential containing the selfinter-

action of the chiral 24-plet has the form

$$W(\Phi(x)) = \lambda[Tr(\Phi(x)^3) + MTr(\Phi(x)^2)] \tag{33}$$

The vacuum solution

$$\Phi(x) = \frac{4M}{3} Diag(1, 1, 1, -\frac{3}{2}, -\frac{3}{2}) \tag{34}$$

leads to the $SU(5) \rightarrow SU(3) \otimes SU(2) \otimes U(1)$ gauge symmetry breaking. After the gauge symmetry breaking the octets and triplets acquire a mass $m_8 = m_3 = 10\lambda M$. So in general superoctet and supertriplet masses don't coincide with M_v and in fact they are free parameters of the model. It is possible to have grand unification scale $M_v = 5 \cdot 10^{17} Gev$ and $M_{SUSY} \leq 1 Tev$ [23] provided octets and triplets are lighter than the vector supermultiplet by factor 15000 that is welcomed from the superstring point of view [35].

It is interesting to mention that it is possible to have $M_v \sim 5 \cdot 10^{17} Gev$ and $M_{SUSY} \leq 1 Tev$ by the introduction only relatively light octet with a mass $m_8 \sim 5 \cdot 10^8 Gev$. To satisfy the relation (2) we have to introduce 4 additional light superdoublets with masses $O(10)$ Tev. The phenomenology of such models has been considered in ref.[36]. Such models allow to have big Yukawa couplings for all generations. The smallness of the quark and lepton masses of the first and second generations is related with the smallness of the corresponding vacuum expectation values [37].

In conclusion let us formulate our main results. In standard SU(5) supersymmetric model we have calculated the masses of vector supermultiplet and of the Higgs supertriplet. We have found that in standard supersymmetric $SU(5)$ model with coloured octet and triplet masses $O(M_v)$ and with equal gaugino masses at GUT scale the nonobservation of the proton decay leads to the upper bound $M_{SUSY} \leq 50$ Tev on the supersymmetry breaking scale and to the lower bound $m_{\tilde{q}} \geq 1460$ Gev on the squark mass. For the case when octets and triplets have the masses $O(M_{SUSY})$ it is possible to increase the supersymmetry breaking scale up to $O(10^{12}) Gev$, however in this case in order to satisfy the equation (2) for the superhiggs triplet mass we have to introduce 4 additional relatively light superhiggs doublets. We have demonstrated also that in standard SU(5) model it is possible to have GUT scale $M_v \sim 5 \cdot 10^{17}$ Gev and supersymmetry breaking

scale $M_{SUSY} \leq 1$ Tev provided that octets and triplets are lighter than vector supermultiplet by factor $O(15000)$. We have found that it is possible to construct supersymmetric SU(5) model with 6 relatively light Higgs superdoublets and the superoctet with a mass $m_8 \sim 5 \cdot 10^8$ Gev. In the extraction of the bound on the value of M_{SUSY} our crusial assumption was the inequality [5] $M_3 \leq 3M_v$. The obtained bound on the M_{SUSY} depends rather strongly on the details of the high energy spectrum (on the splitting between octet and triplet masses) and on the splitting between gaugino masses. It should be noted that for $M_{SUSY} \geq O(1)Tev$ we have the fine tuning problem for the electroweak symmetry breaking scale.

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